Field Test of a Photovoltaic Water Heater

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Performance of Service Water Heating Systems: Some Actual Results

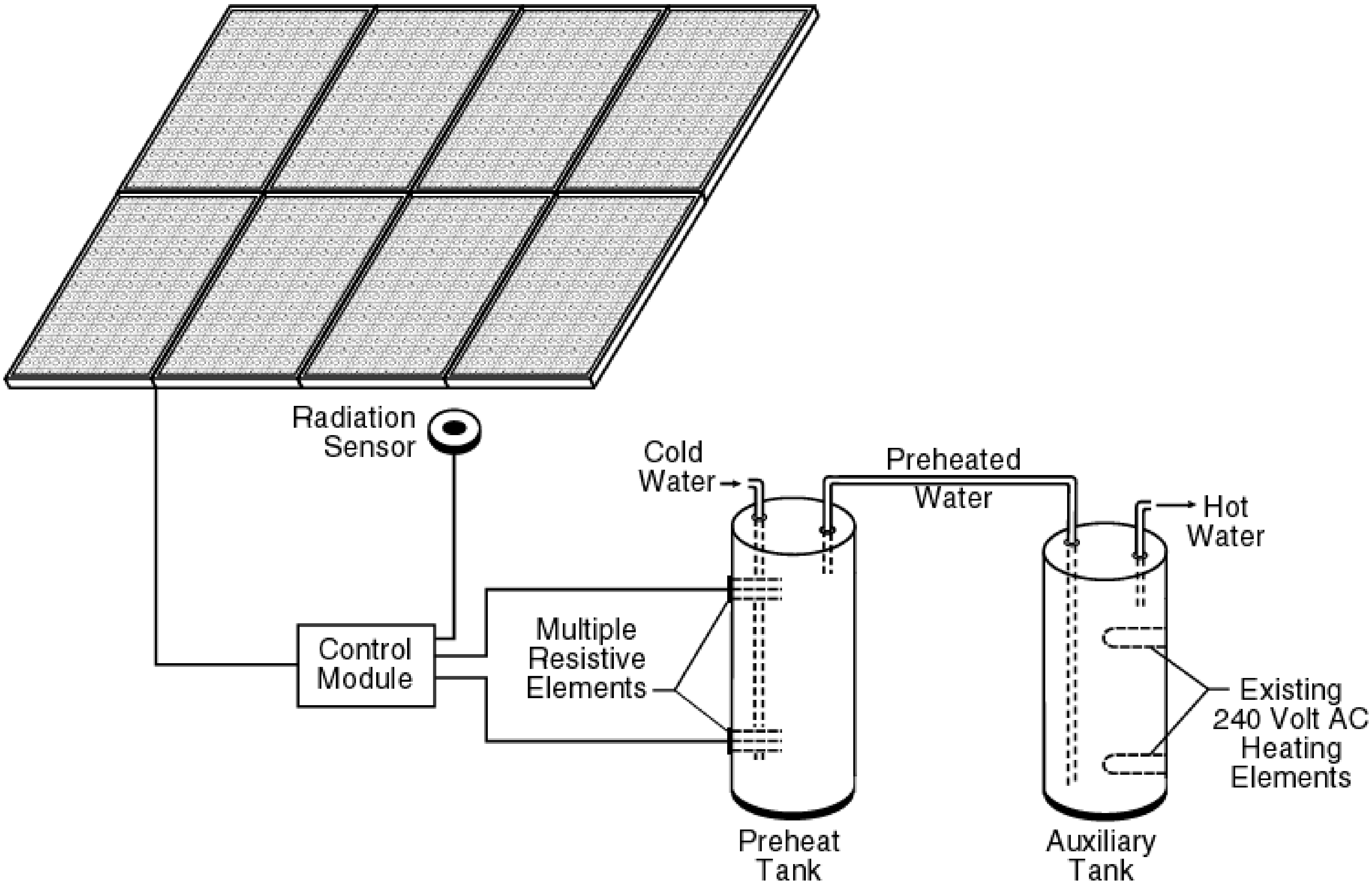
SCOPE

- ***Background***
- ***Description and Operation of a PVWH System***
- ***Field Monitoring***
- ***Results and Discussion***
  - **Solar Photovoltaic System Performance**
  - **Water Conservation Attempts**
- ***Summary***

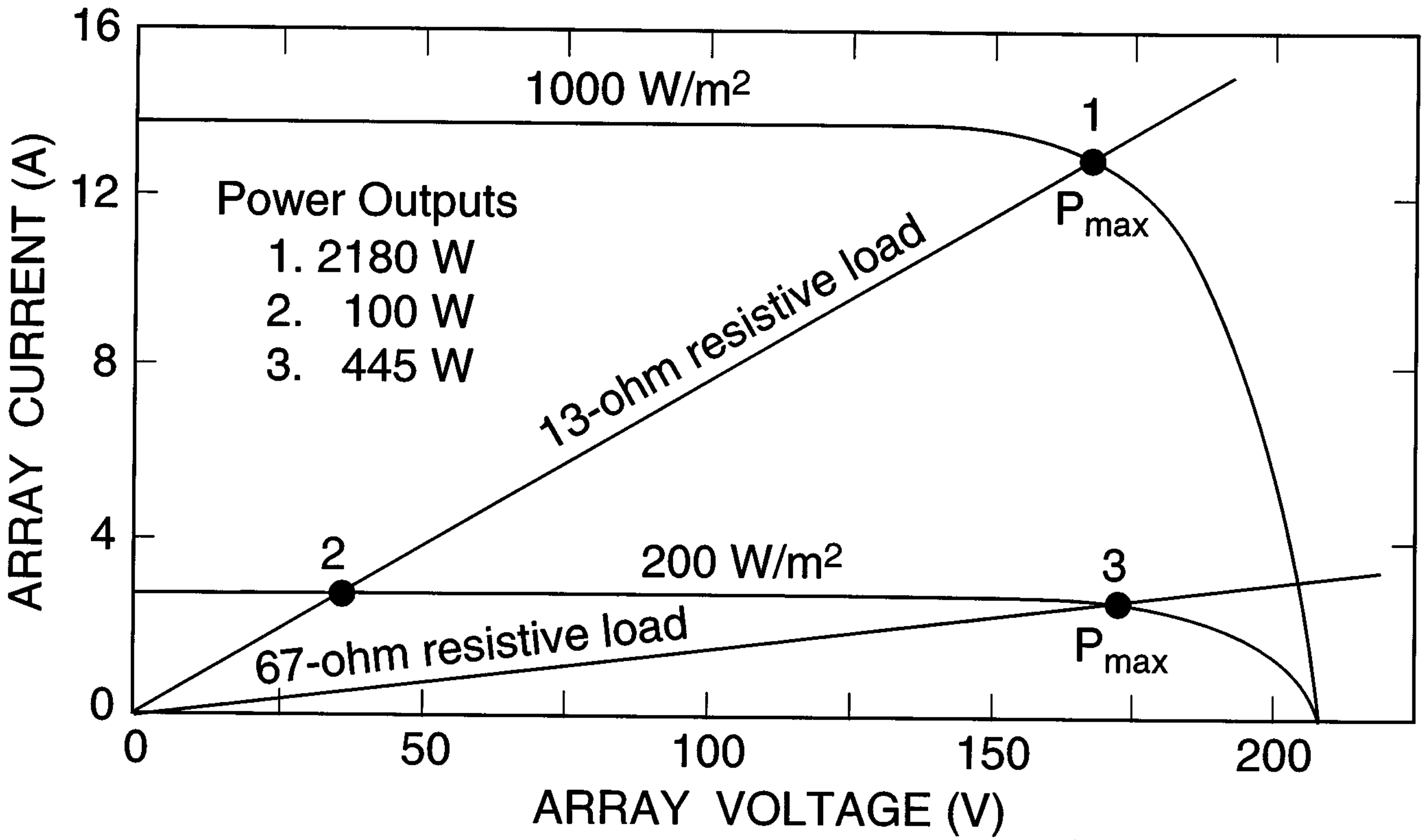
BACKGROUND

- ***Solar PV for Water Heating Patented in 1994***
- ***2 Research Sites; 2 Demonstration Sites***
- ***Demonstration Site: Main Visitor Center at the Great Smoky Mountains National Park***
- ***Initial Goal: Install and Monitor PVWH System***
- ***Add-on Goal: Reduce Hot Water Consumption***

Two-Tank PVWH Schematic



PHOTOVOLTAIC ARRAY CURRENT VERSUS VOLTAGE CHARACTERISTICS



- Rated Power Output: 2120 W_{peak}
- Modules Use Single Crystalline Silicon Cells
- 23° Tilt Facing True South; 35.5° North Latitude

- ✡ Uses 6 PV Heating Elements
- ✡ Auxiliary Tank Setpoint Between 41 and 45°C
- ✡ Supply Bathroom Facilities
- ✡ Installed: September 1996
- ✡ Monitored: 11/96 to 2/00

Monitoring Intervals

Solar Photovoltaic (Only) System Performance

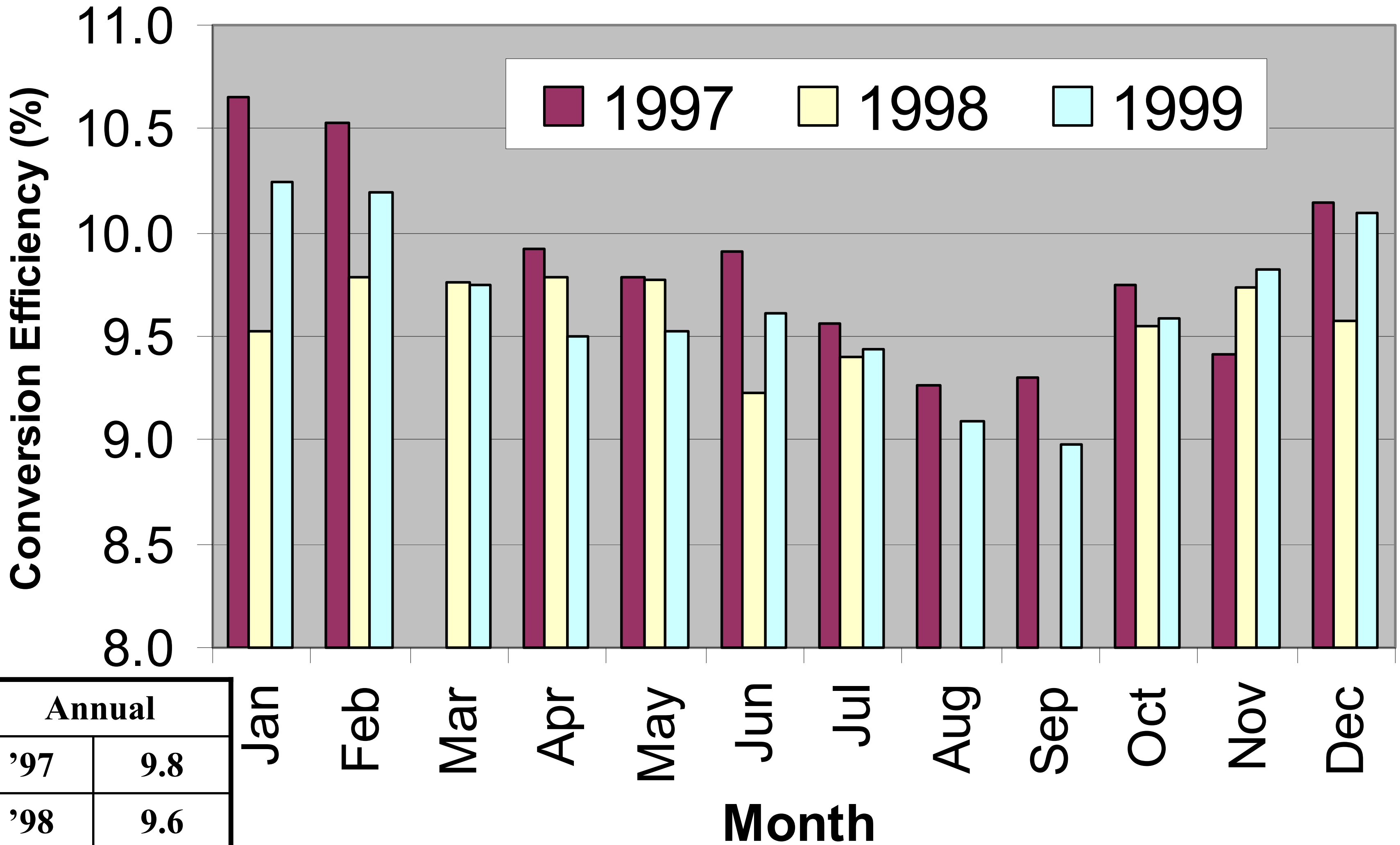
- *Conversion Efficiency and PV Energy Production*
- *Monthly and Annual ('97, '98, and '99) Performance*

Water Conservation Performance

- *Hot Water Usage and Electrical Fraction*

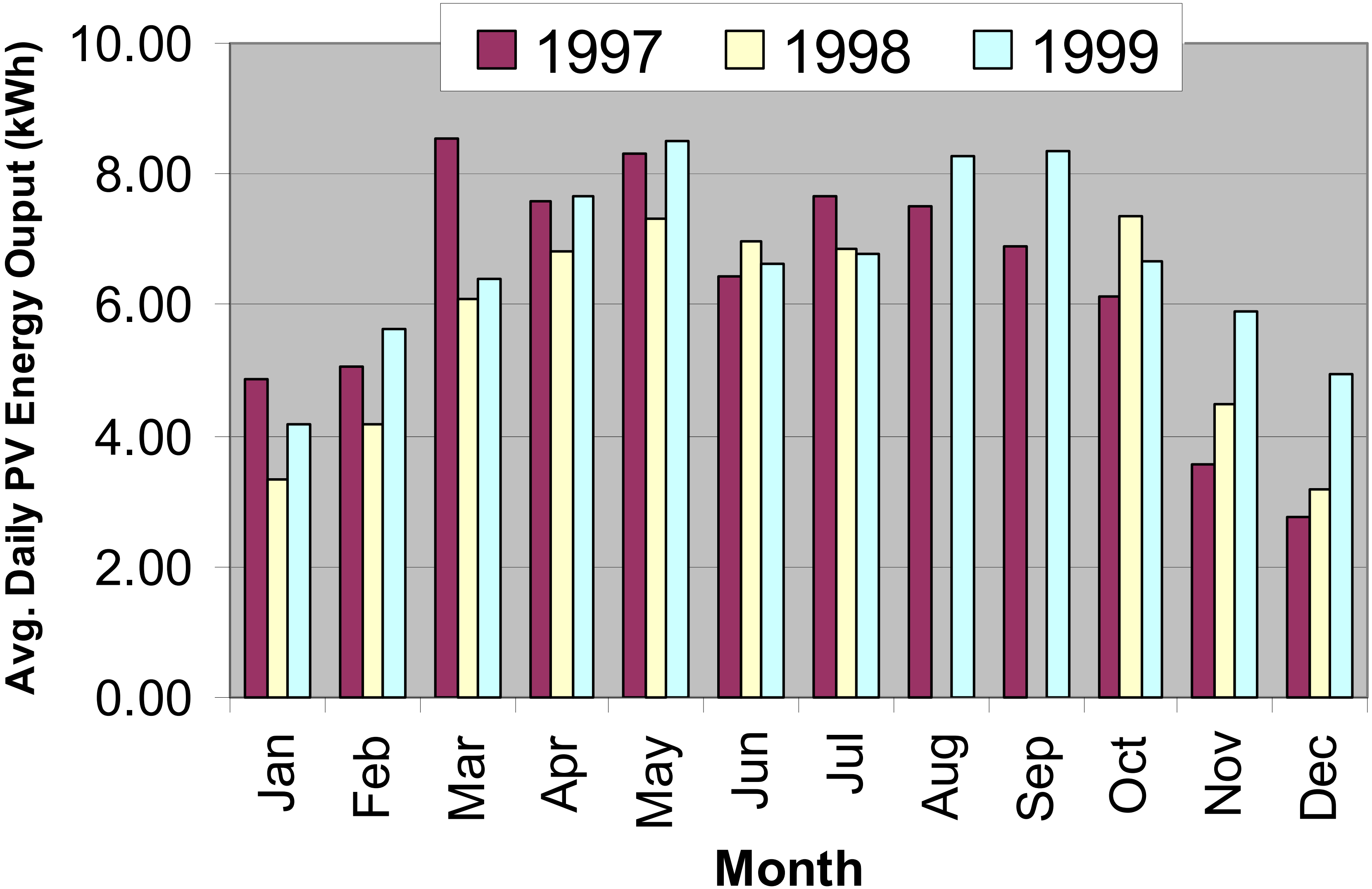
Configuration	Type of Faucet	Aerator Rating	Interval
I	Manual	17 L/min (4.5 gpm)	11/1/96 – 10/1/97
II	Manual	8.3 L/min (2.2 gpm)	10/3/97 – 10/18/98
III	Automatic	8.3 L/min (2.2 gpm)	10/27/98 – 3/8/99
IV	Automatic	1.9 L/min (0.5 gpm)	3/10/99 – 2/29/00

PVWH System Conversion Efficiency

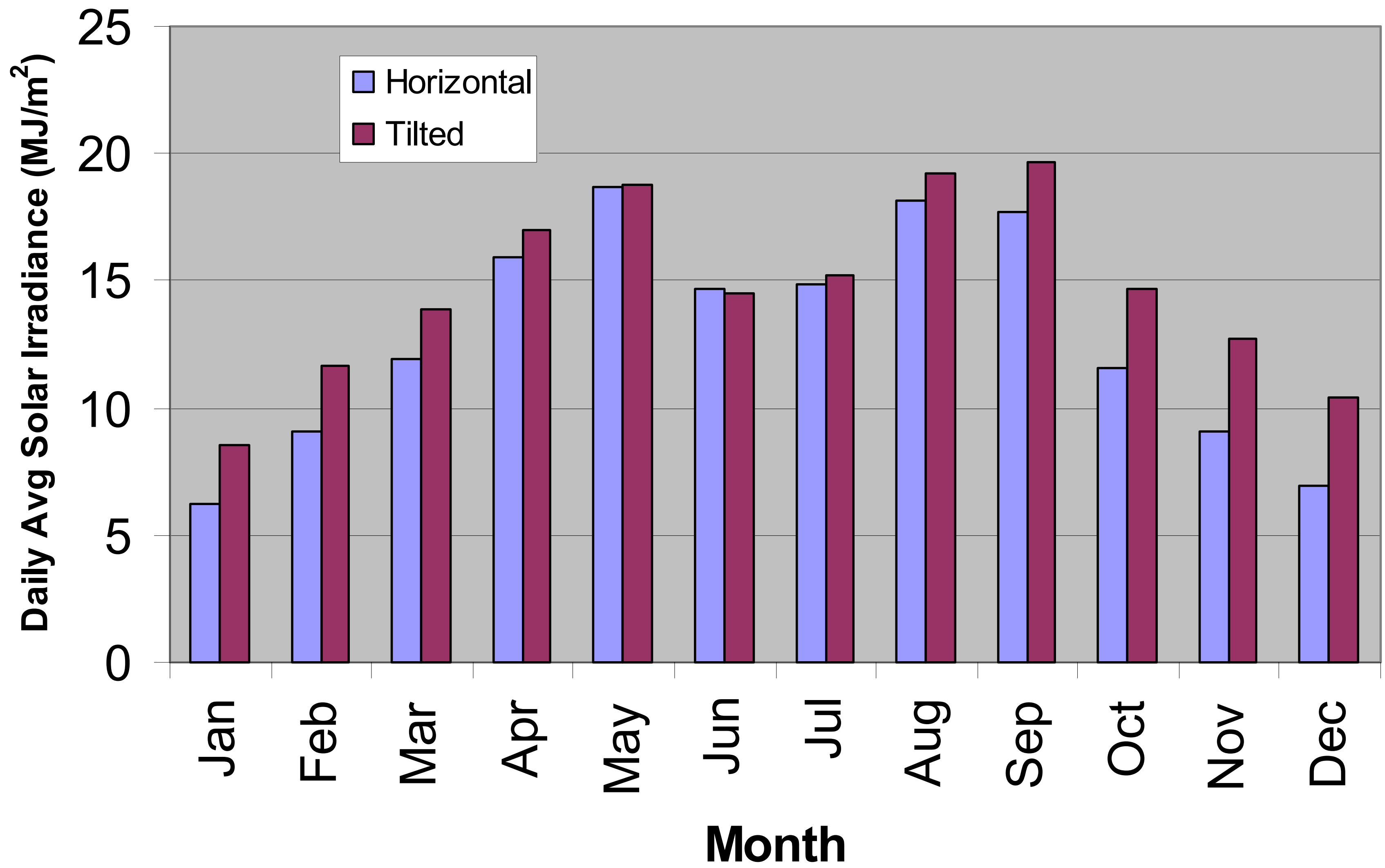


Annual	
'97	9.8
'98	9.6
'99	9.6

PVWH System Delivered Energy



Local Solar Resource (1999 Data)



Comparisons With Other PVWH Field Sites

PVWH System	PV Array Rated Output (W)	PV System Conversion Efficiency (%)	Annual PV Energy Production (kWh)	Annual Energy Production to Array Rated Output (kWh/W_{peak})	Average Daily Solar Irradiance (MJ/m^2)
GSMNP	2120	9.7	2245	1.06	13.42
NIST 2-Tank	1590	11.0	2243	1.41	15.75
NIST 1-Tank	1590	10.6	2190	1.38	15.87
FSEC 2-Tank	1431	10.0	2177	1.52	18.57
FSEC 1-Tank	1060	10.2	1613	1.52	18.27
Okinawa I	1272	—	1487	1.17	—
Okinawa II	1272	—	1522	1.20	—

Comparison Case: PV Module Rated Efficiency = 12.4%

Water Conservation Efforts

Water Conservation Efforts

	Daily Hot Water Use L/day (gal/day)		Electrical Fraction		Park Attendance: People per Day	
	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov
I	742 (196)	351 (93)	30.2	34.7	9360	4710

➔ Park personnel:

- ❖ satisfied with PV water heating system
- ❖ very interested in reducing their water/sewer bill

➔ Let's try changing the aerators: 17.0 vs. 8.3 L/min

Water Conservation Efforts

	Daily Hot Water Use L/day (gal/day)		Electrical Fraction		Park Attendance: People per Day	
	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov
I	742 (196)	351 (93)	30.2	34.7	9360	4710
II	764 (202)	372 (98)	26.8	28.3	10290	4710

➔ Conclude: replacement aerators had little impact

➔ Let's try automatic faucets; same rated aerator

Water Conservation Efforts

	Daily Hot Water Use L/day (gal/day)		Electrical Fraction		Park Attendance: People per Day	
	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov
I	742 (196)	351 (93)	30.2	34.7	9360	4710
II	764 (202)	372 (98)	26.8	28.3	10290	4710
III	—	586 (155)	—	25.2	—	5750

➔Wrong direction! ➔Try low-flow aerator: 8.3 vs. 1.9 L/min

Water Conservation Efforts

	Daily Hot Water Use L/day (gal/day)		Electrical Fraction		Park Attendance: People per Day	
	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov	Entire Interval	Feb – Nov
I	742 (196)	351 (93)	30.2	34.7	9360	4710
II	764 (202)	372 (98)	26.8	28.3	10290	4710
III	—	586 (155)	—	25.2	—	5750
IV	466 (123)	244 (64)	59.7	—	10400	5690

Water Conservation Efforts

Success At LAST!!

Summary

- PVWH Installed Sept. 1996 at Park
- PV System Conversion Efficiencies
  - Consistent from year to year
  - Monthly: vary from 9.0 to 10.7%
- Local Solar Resource Drives PV Energy Output
  - Peaks in mid Spring and late Summer
  - Poorer solar gain versus other field sites

Summary

- ***Low-flow aerators work***
  - ***Acceptable for hand washing***
  - ***Saves water . . . which saves energy***
    - ***Hot water use decreased 37% (while attendance was slightly higher)***
    - ***Less AC auxiliary energy required; percentage of energy supplied by PV array doubled***

- ***Automatic faucets are a convenience, not an water/energy saver***

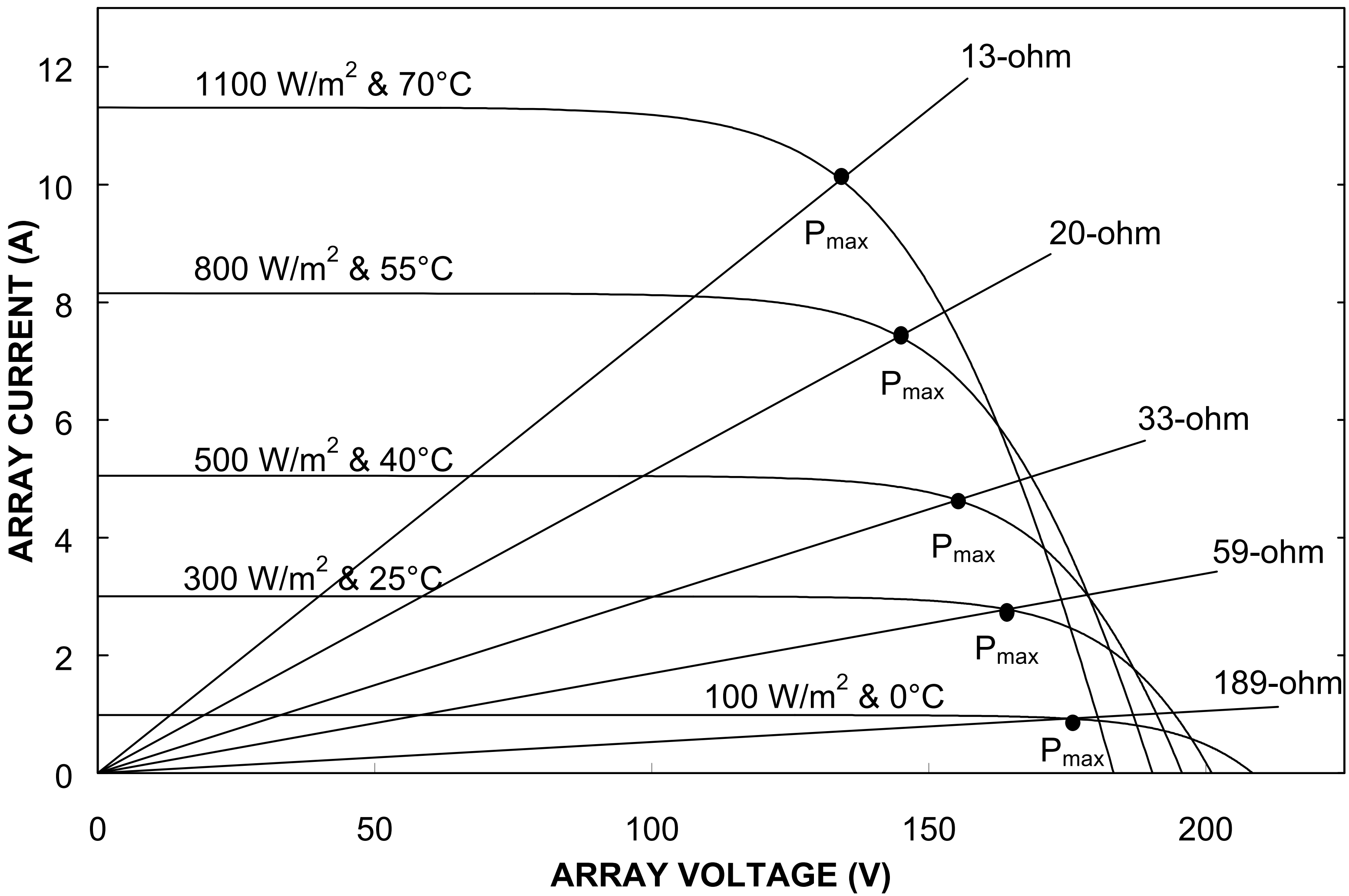
Overall Experiences With the Technology

- *17 years of operation among the 7 installations*
  - *Robust performance for prototype systems*
  - *6 cases of reduced PV energy generation (no complete failures)*
    - *Shifted resistance element (51 ohms to 78 ohms)*
    - *Faulty PV module (1 out of 145)*
    - *Loose fuse for one string of modules*
    - *Failed electrical connection at module junction box*
    - *AC power cord to PVWH controller accidentally unplugged*
    - *Tripped storage tank's high temperature limit thermostat*

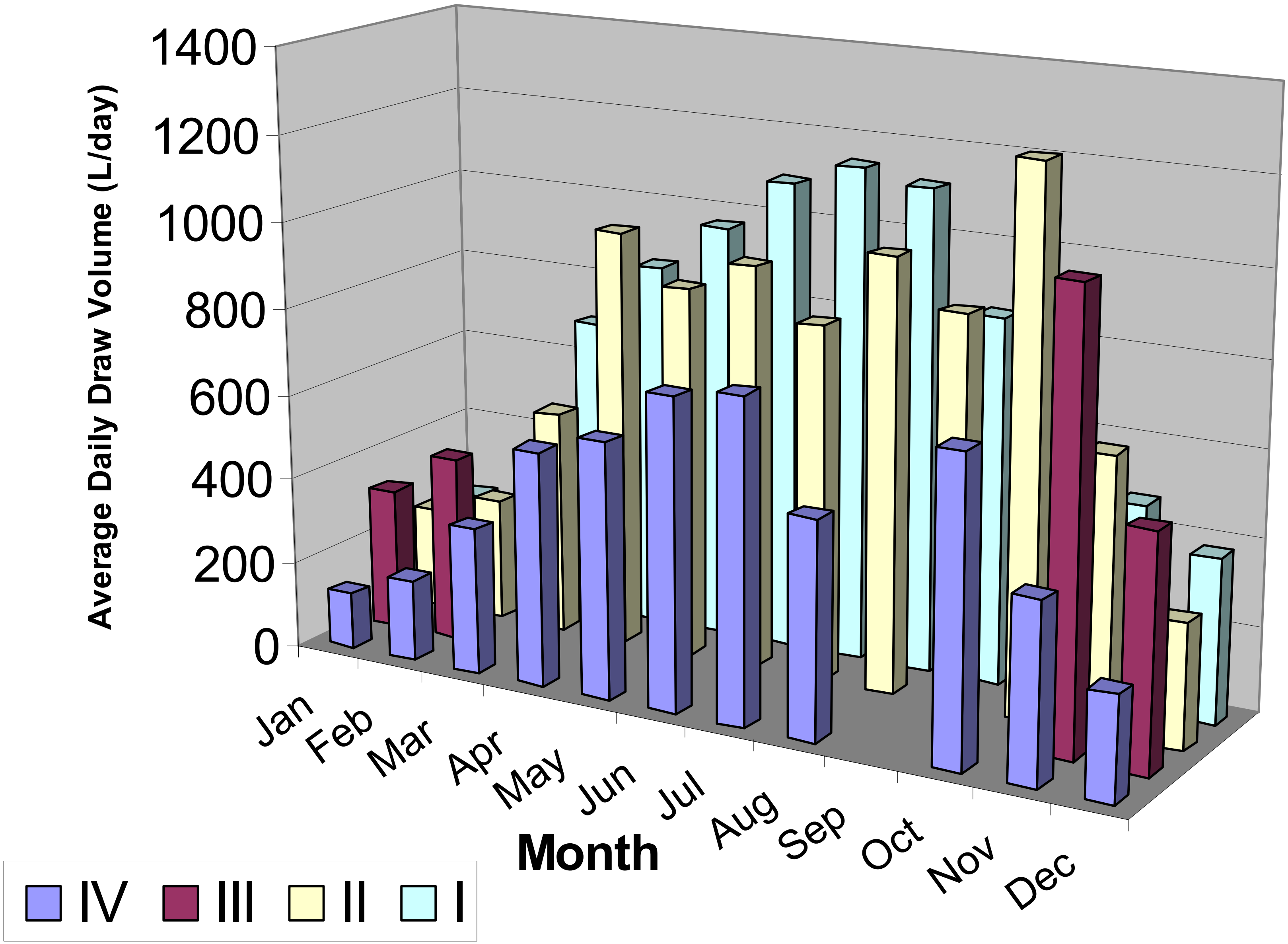
- *Applicable to two-tank and single-tank configurations*

- *Potential market if the $/W$_{peak}$ drops to the $1.50-$2.00 range*

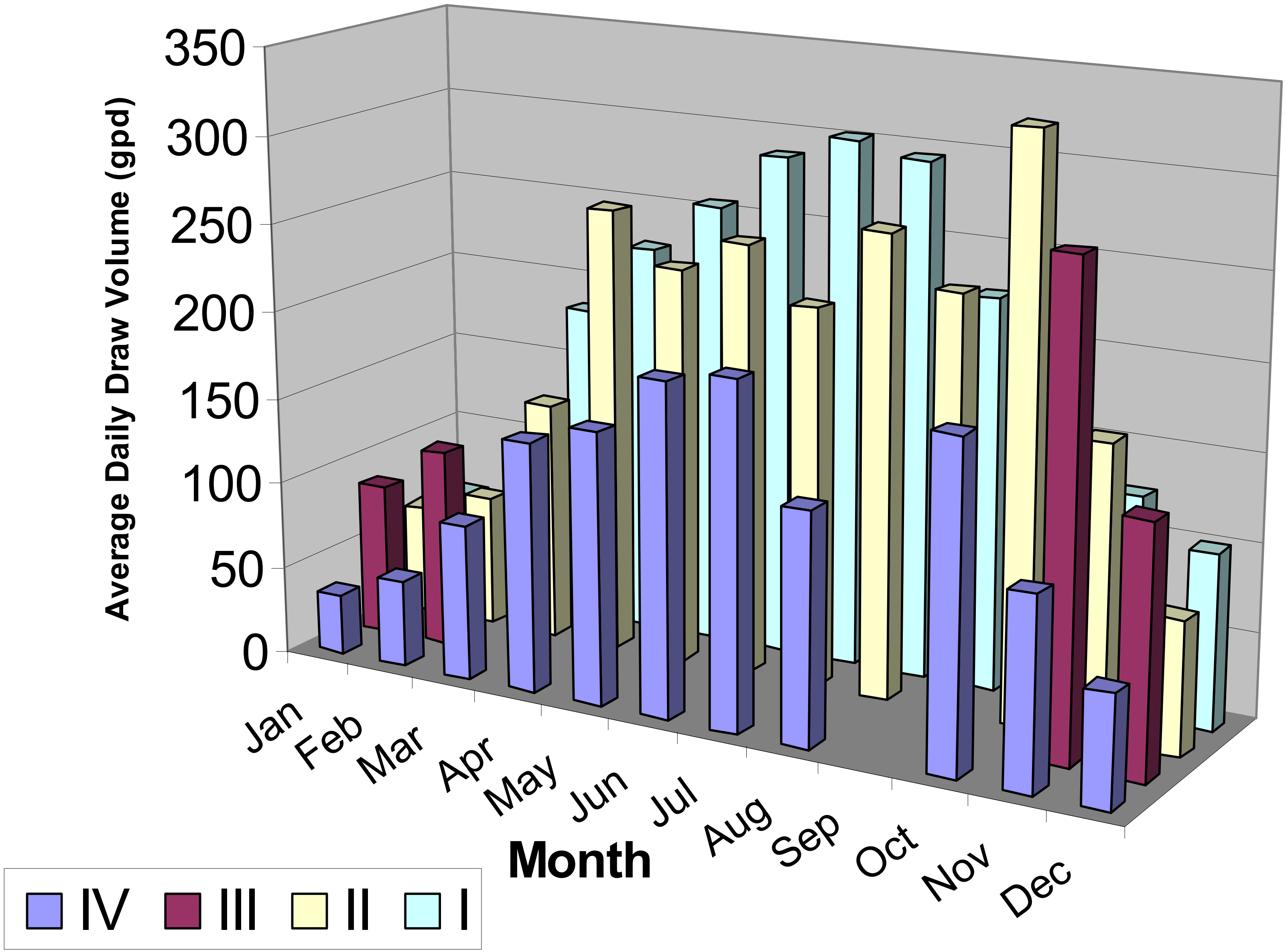
PV Array I-V Curves with Load Lines



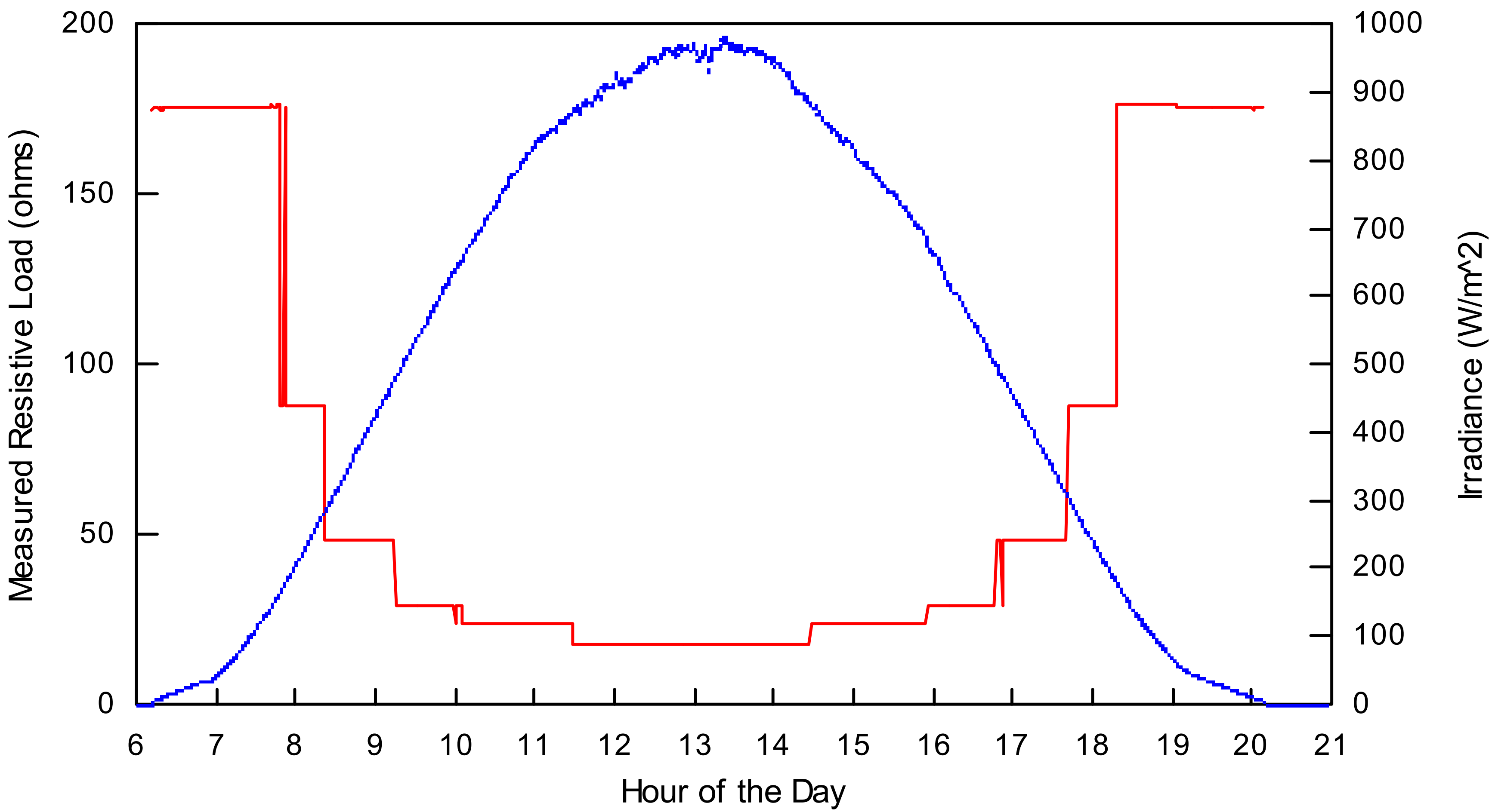
Daily Hot Water Consumption



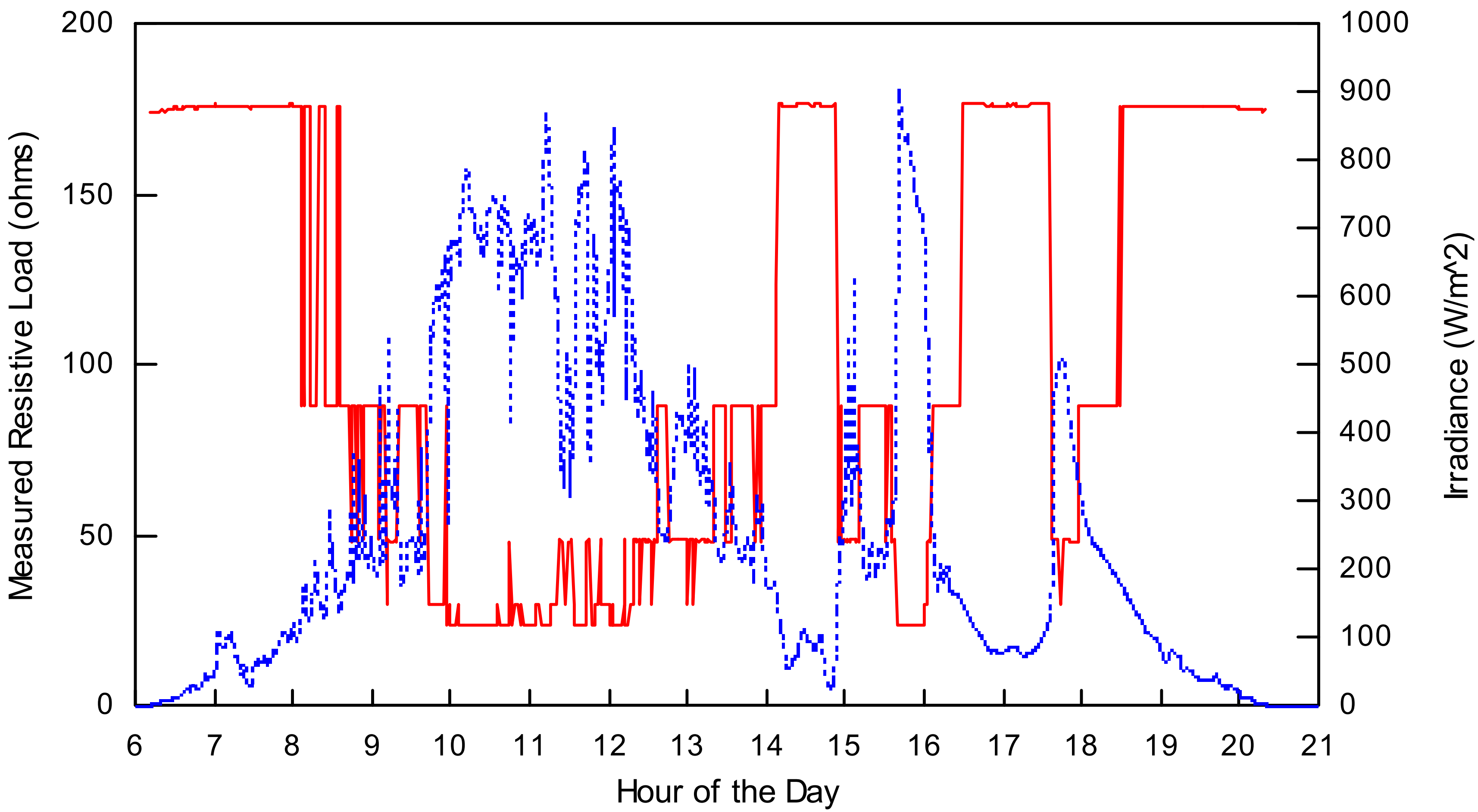
Daily Hot Water Consumption (IP)



Resistive Load Variation: Clear Day



Resistive Load Variation: Cloudy Day



PVWH Versus Solar Thermal Water Heating

- **Advantages of Solar Thermal Water Heating**
  - **Lower initial cost (but gap is narrowing)**
  - **Higher conversion efficiency/smaller solar collector area**
- **Disadvantages of Solar Thermal Water Heating**
  - **Freeze protection contingencies for many locations**
  - **Lower reliability/life expectancy; higher maintenance costs**
  - **Pipes and fluids versus wiring and DC current flow**
  - **Less aesthetically pleasing**
  - **Comparatively less promise for efficiency increases and manufacturing cost decreases**
- ***Key Question: Can the PV Industry Reduce the Cost of PV to the $1.75/W_p$ Range?***

PVWH Versus PV Grid-Connected

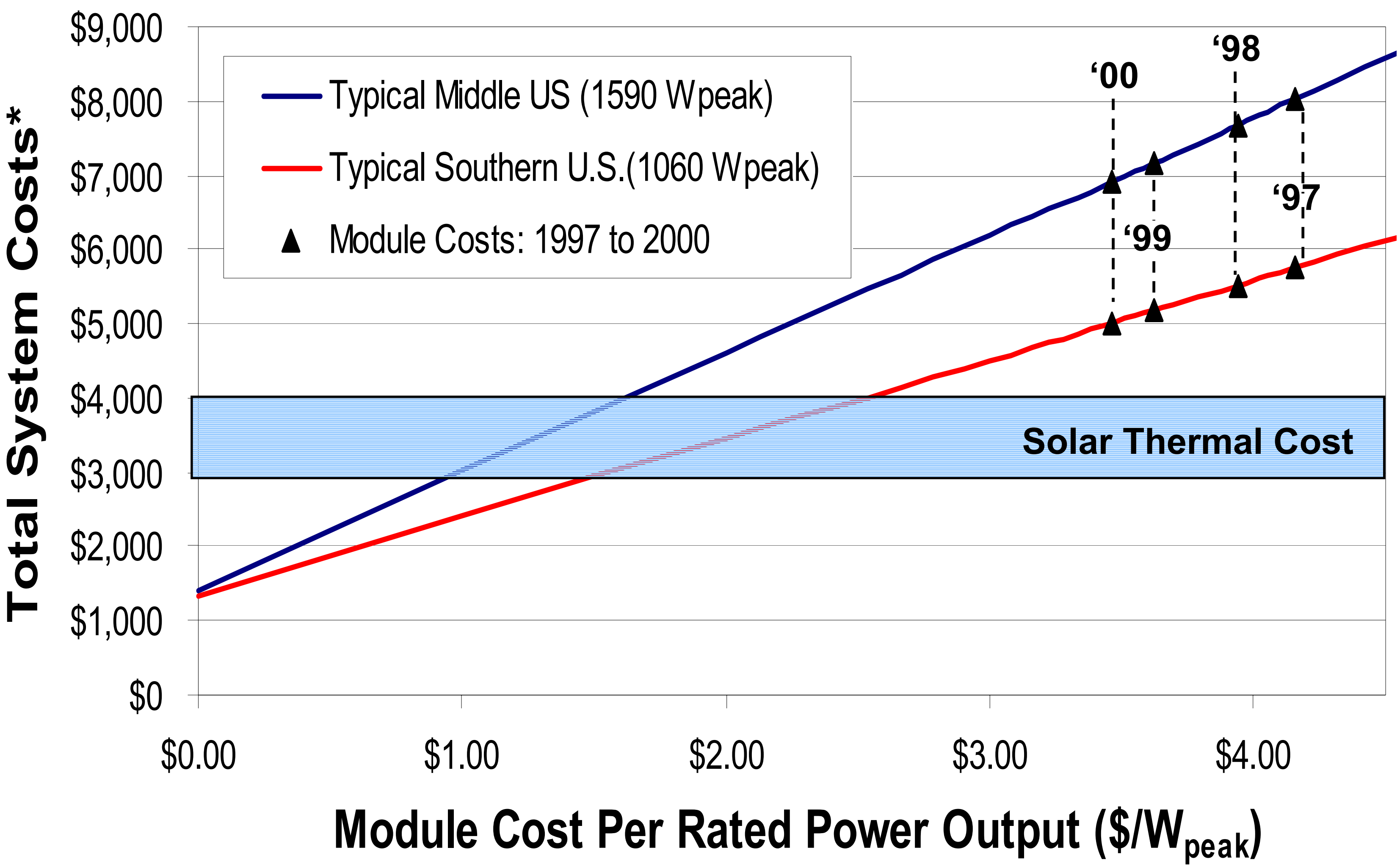
- **Advantages of PV Grid Connected**
  - Flexibility for multiple end uses
  - Potential for higher solar utilization

- **Disadvantages of PV Grid Connected** (although improving)
  - Higher balance-of-system costs
    - \$0.75 to 1.70 $W_{peak\ AC}$ for inverter (1 to 2.5 kW)
    - \$400 to \$450 for the PVWH controller, radiation sensor, and 2 PV heating element assemblies
  - Comparatively lower reliability; higher maintenance costs
  - Slightly lower conversion efficiencies
  - Greater burden: permitting, interconnecting,,& inspection

PVWH Versus PV Grid-Connected: A Favorable PVWH Scenario

- **PV Array Size: 750 to 2500 Watts Peak**
- **Moderate to High Hot Water Consumption**
- **Hot Water Consumption is Regular Throughout the Year**
- **End User Otherwise Heats Water Using an Electric Resistance Water Heater (As Do 45% of the Homes in the US)**
  - ***-Avoid the cost, complexity, and loss of efficiency of converting DC array power into AC grid power and then using it to resistively heat domestic water***

Hot Water System Initial Cost

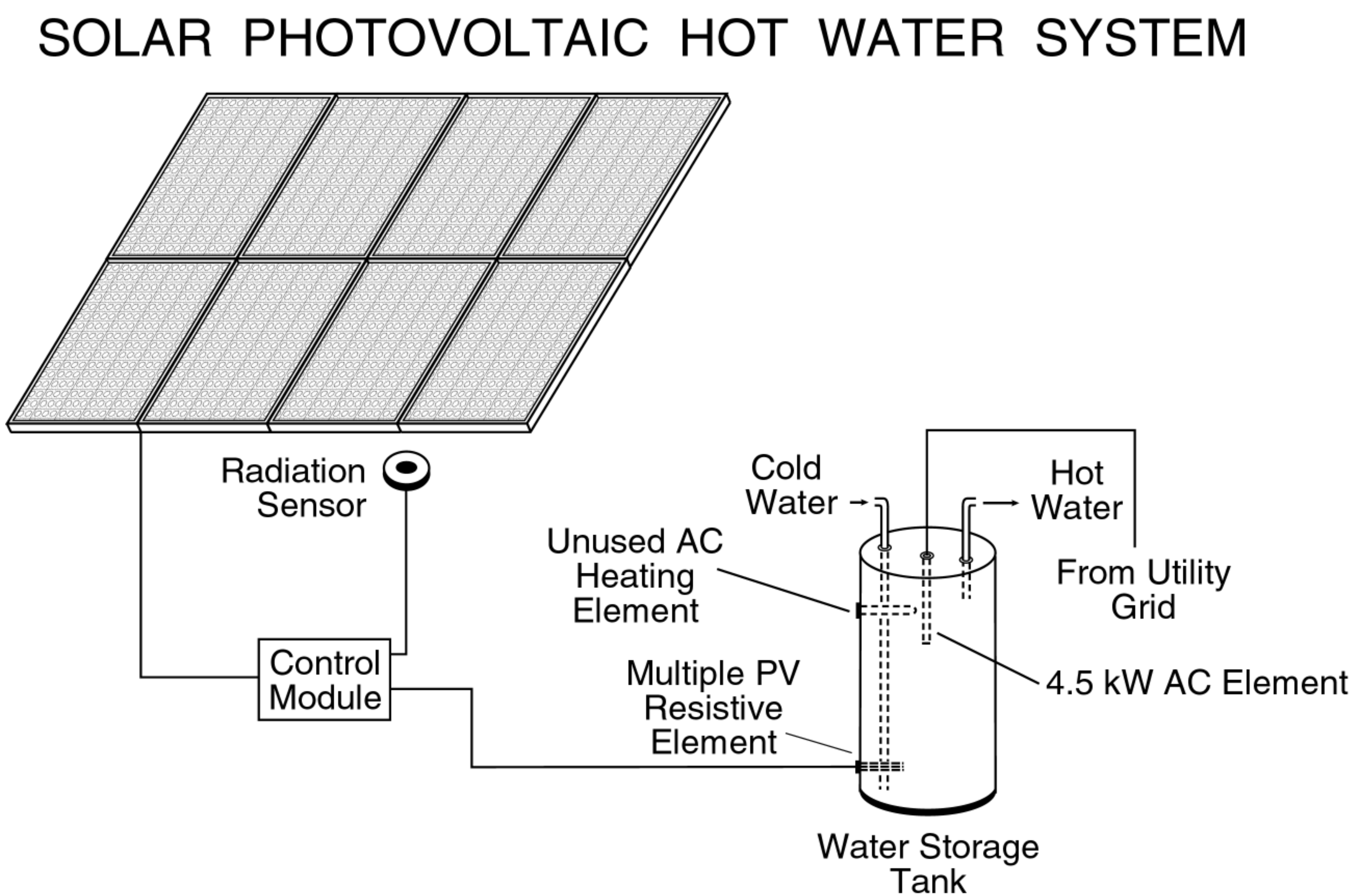


*Includes installation and balance of system costs

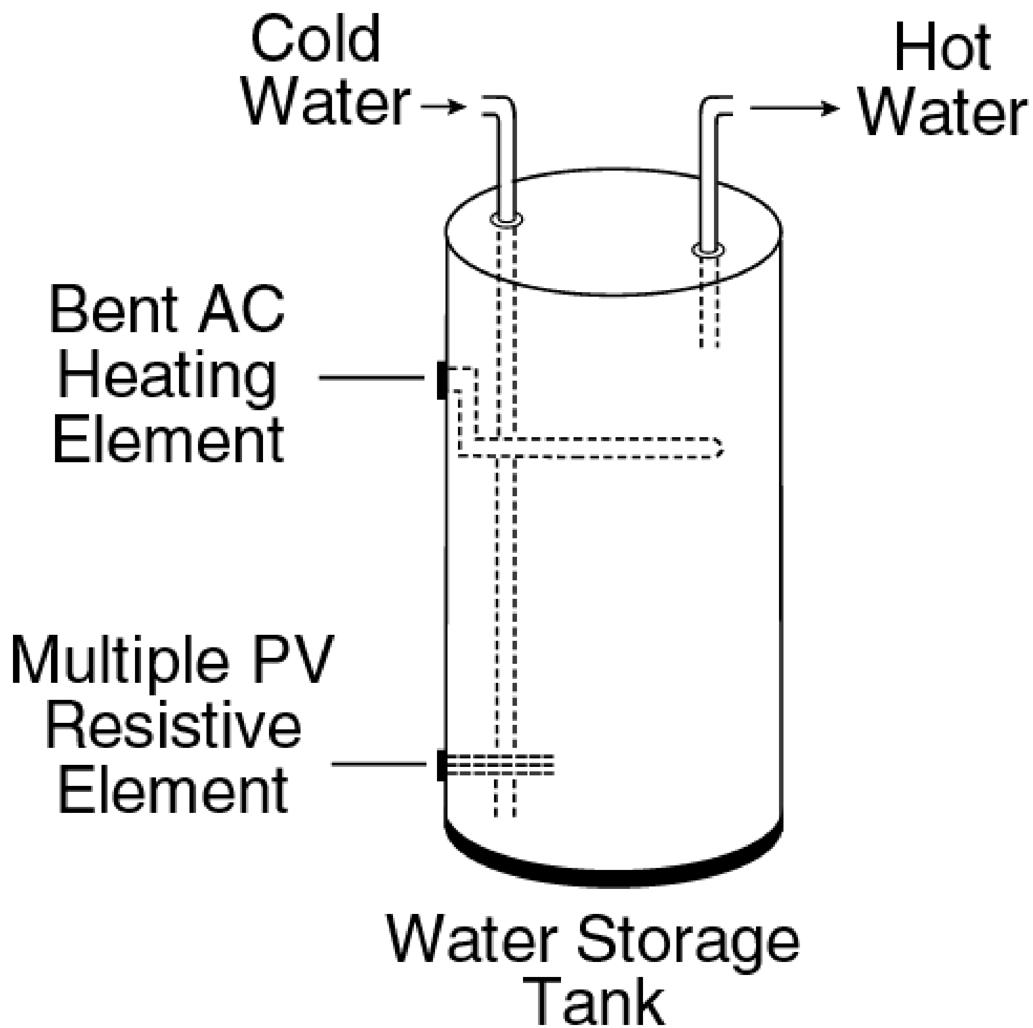
Research and Demonstration Sites

- **NIST (Research)**
  - Two-tank systems
  - Single-tank system
- **FSEC (Research)**
  - Two-tank system
  - Single-tank system
- **Great Smoky Mountain National Park (Demonstration)**
  - Two-tank system
- **Kadena Air Force Base, Okinawa, Japan (Demonstration)**
  - Two installations
  - Both two-tank systems

Single-tank PVWH Schematic



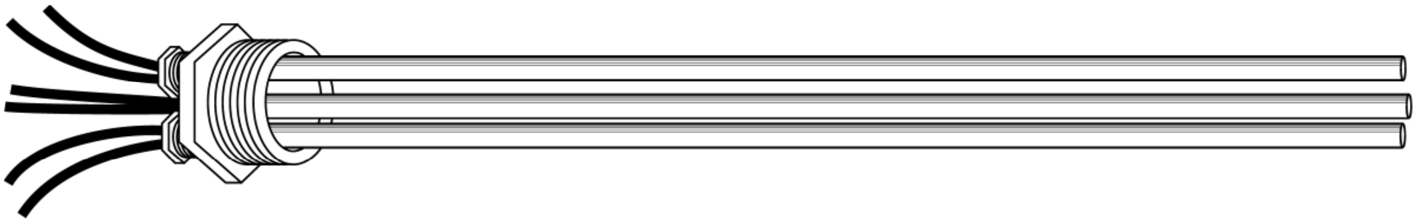
Alternative Single-tank Design: Bent AC Element

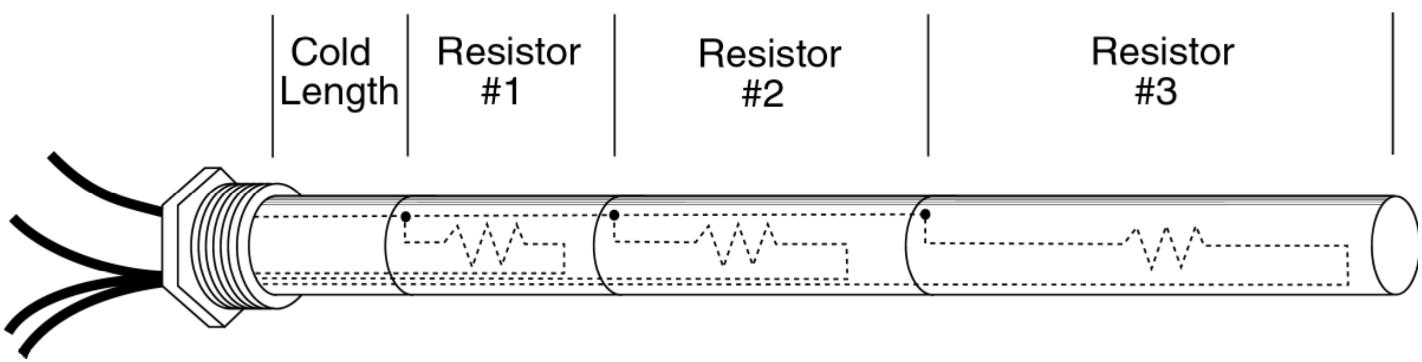


PV Water Heating System Components

- ***Typically 750 to 2500 Watt photovoltaic array***
  - *Array areas: 6 to 20 m^2 (64 to 216 ft^2)*
- ***Unique Balance-of-System Components***
  - *Control Module*
  - *Solar Radiation Sensor*
  - *PV Resistive Element Assemblies (1 or 2)*
  - *Two-element electric water heater (1 or 2)*
- ***Balance-of-System Components Avoided***
  - *DC-to-AC Inverter*
  - *Storage Batteries*
  - *Maximum Power Tracking Power Conditioning Electronics*

PV Multiple Heating Element Assemblies





PV Water Heating System Rationale

- ***Off-grid Application for Using Photovoltaic Energy***
- ***Use DC Energy From PV To Directly Heat Domestic Water***
- ***Use Multiple In-Tank Resistive Elements to Operate Photovoltaic Array At or Near Its Maximum Power Point***
- ***Use Water As The Energy Storage Device / System Flywheel (Versus Batteries or the AC Grid)***